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New High Performance, Low GWP Refrigerants for Stationary AC and Refrigeration

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ABSTRACT

In response to concerns about global climate change, and in consideration of probable legislation that may impact the production and use of refrigerants with high global warming potential, a set of new refrigerant candidates has been developed for evaluation. Some candidates are designed for stationary air conditioning in residential and light commercial end uses. Other refrigerant candidates were designed more specifically for use in medium temperature refrigeration applications. These candidates all have GWP values that are reduced significantly from R-134a, R-410A and R-404A values, and have good predicted performance characteristics as determined by cycle modeling. Model results must always be validated by actual system tests, and that work has been underway for some time now. System tests are indeed showing that the predicted model results are achievable. This presentation will describe these candidates and show some results from evaluations of their cooling and heating performance properties and LCCP (Life Cycle Climate Performance) comparisons.

1. INTRODUCTION: THE NEED FOR NEW REFRIGERANT GASES

There is little doubt among scientists that the earth's climate is undergoing unexpected changes. Mitigation of climate change and the causes thereof could impact many sectors of business and industry, as well as our personal lives as we work to find ways to decrease the impact of human activities on our environment. Energy generation and use for industry, transportation, lighting, and climate control are major contributors to carbon dioxide (CO_2) in the earth's atmosphere. In addition, certain fluorinated gases that have been used for refrigeration and other beneficial purposes have been found to have direct global warming potentials much higher than $CO_{2,\ \mathrm{if}}$ they are released into the atmosphere. The benefits that refrigeration, air conditioning, and heat pumps bring to our lives are highly valued, so there are increased efforts to identify new methods to achieve cooling using materials that do not depend on high GWP working fluids. These efforts are yielding success.

The field of refrigeration broadly covers a wide diversity of systems of different physical sizes and ranges of thermodynamic operating requirements. There is no single refrigerating or heat pump fluid that has been found to serve efficiently and safely in all of types of systems. There is still a need for fluids with the appropriate physical and thermodynamic properties to be used most efficiently in each given set of operating conditions, especially if current equipment and equipment designs are to be used and environmental impact minimized. Wholesale abandonment of current equipment types would be disruptive and unsustainably resource intensive. A more balanced, environmentally sustainable solution is to identify reduced GWP working fluids that allow existing equipment to continue to be used, so long as the equipment uses no more energy, and measures to minimize accidental loss of the working fluid are taken. The most desirable case is if the working fluid, if it is leaked, it must have minimal impact on the climate. However, if a fluid does not have the optimal properties for the machine in which it is used, it is likely to result in inefficient operation. Much more energy would be used in the operation of the system than if an optimum fluid were used (Downing, 1988).

This paper describes some novel, reduced GWP, refrigerant candidates and some of their properties. Also discussed are some of the trade offs involved in selecting refrigerant candidates best suited to specific applications. Results of refrigeration cycle modeling and equipment testing for several applications are presented and discussed.

2. DEVELOPMENT OF NEW REFRIGERANTS

Continuously improving understanding of societal needs and values, along with ever improving understanding of our planet and its environment have prompted searches for better refrigerants. Regardless of what refrigerant is used, environmental and safety impacts can be minimized by proper stewardship of the refrigerant. Proper management and utilization of refrigerant gas to prevent leakage is critical. This includes equipment design and manufacturing processes to minimize the possibility of leakage. The practice of refrigerant management techniques for recovery, reclaim, and recycle of refrigerants during service or decommissioning of systems can ultimately reduce climate impact from refrigeration. However, it is still important to use refrigerants that allow minimum energy use with a minimum charge size of refrigerant, and that present minimal risk if accidently released.

2.1. A New Low GWP Refrigerant: HFO-1234yf

A new class of refrigerants has been developed initially for use in automobile air conditioning systems. The class is partially fluorinated olefins, and the best known example is hydrofluoroolefin 2,3,3,3-tetrafluoroprop-1-ene, or HFO-1234yf (Minor and Spatz, 2008). While this molecule has been found to be a good refrigerant in medium temperature applications, its volumetric capacity properties are not optimal for other applications, including stationary air conditioning and low temperature commercial refrigeration (Leck, 2009). While it has excellent environmental properties (Nielsen *et al*, 2007), the fact that it can be made to burn, albeit with limited energy release and limited flame propagation rate (Wilson and Leck, 2008) will require some regulatory and building code review and modification to define safe use conditions.

Systems that require high refrigerating capacity perhaps could be redesigned to use a fluid like HFO-1234yf, but system re-engineering, design, and performance compromises would be required. Larger compressors likely would be necessary to deliver the mass flow rate of refrigerant to achieve a comparable rate of cooling. The larger compressors and larger piping necessary to circulate the required volumes of refrigerant without incurring excessive pressure drop losses would require that more metal and energy be used to fabricate these systems. The production of the required metal and the fabrication of the larger units have their own environmental and atmospheric costs in terms of carbon emissions and other impacts of metal mining and processing. It may be necessary to operate outside of the optimum conditions for the refrigerant. That would likely lead to more energy consumption during operation of the equipment. Greater energy consumption often results in more CO_2 generation during power generation. The increased physical size of such units could be a limitation as to where such re-designed systems could be installed and used.

The use of even mildly flammable refrigerants requires compliance with safety standards and laws, such as building codes and standards for equipment design. Because it contains fluorine, the burning characteristics of HFO-1234yf are mitigated greatly compared to hydrocarbon compounds (Minor and Spatz, 2008). However, because it can be made to burn, it must be classified and managed as a flammable material. This is an issue in many public areas, such as supermarkets where many customers can be present, and in residential applications, where safety requirement compliance is mandated. Some non flammable options and their limits are therefore discussed.

2.2. New Refrigerant Candidates for Stationary AC and Refrigeration Applications

We have developed some improved refrigerant candidates that leverage the environmental benefits of HFO-1234yf, while addressing the issues of volumetric capacity and in some cases, flammability limitations of the pure compound. Candidates have been developed to illustrate the benefits that can be realized, and also the compromises, or trade-offs, that need to be considered for selected applications. These refrigerant candidates are intended to help define trade offs in the ranges of GWP options and resulting refrigerant performance.

It must be emphasized that this is not advocating commercialization of this entire array of refrigerant candidates. Rather, these are examples to illustrate the ranges of improved properties that can be achieved. Similarly, these illustrate some of the trade offs that are involved, and how property choices could be impacted by certain regulatory structures, such as a low GWP cap. Some of these candidates are currently being evaluated in commercial and residential systems, and if results are satisfactory this could lead to commercialization in the future. To simplify the discussion, some candidates with similar properties have been grouped into ranges of composition and performance. Candidates have been developed at various GWP levels for comparison purposes. For now it is important to understand the range of performance benefits that can be achieved, and to consider these potential benefits as regulations are being developed that will impact stationary air conditioning and refrigeration. Ultimately such regulations will determine which refrigerants and also what refrigerant attributes are necessary and acceptable. It is seen in this analysis that some beneficial trade offs, such as better energy efficiency, or drop-in performance match for certain equipment designs, for higher GWP rating can be attained.

3. DISCUSSION OF CANDIDATE REFRIGERANTS

The data tables that follow show examples of some of the illustrative candidates. The tables show performance characteristics that can be attained in three different end use applications: residential air conditioning, heat pump operation, and medium temperature refrigeration. The candidate groups are labeled as Developmental Refrigerants (DR), DR-11, DR-3, DR-4, etc. Compositions of the DR candidates are not being revealed at this time. In each table there are comparisons made to some appropriate incumbent commercial refrigerants that some of the candidates might replace. In addition are performance comparisons to pure HFO-1234yf, due to the low GWP baseline it establishes.

Shown in the tables are theoretical refrigeration cycle model results for some applications. It is noted that theoretical cycle calculations do not give a complete performance picture for a refrigerant. They lack information about some important transport properties, such as heat transfer coefficients, and pressure drop considerations that will ultimately impact energy performance. Because these refrigerants are based on new molecules and compositions, not all of the necessary properties have been measured, so it is not possible to model overall system performance with complete accuracy. However, there are sufficient measured properties to allow high quality refrigeration cycle modeling to be performed. Sophisticated modeling software and data bases such as those contained within REFPROP (Lemmon, *et al.* 2007) represent the state of the art in refrigerant thermophysical property modeling. For this work, REFPROP was used to compare to those refrigerants for which properties are well characterized, e.g. R-134a, R-410A, and R-404A. For HFO-1234yf and for refrigerant compositions that use HFO-1234yf or other novel molecules it is necessary to employ tools that have been developed internally for the thermodynamic modeling. Proprietary software has been developed that is well suited for evaluation of developmental molecules, including refrigeration cycle modeling (Leck, 2009, Yokozeki, 2008). This software is checked and validated by modeling fully characterized commercial refrigerants and comparing with the results from REFPROP. Model results are also validated by comparing with measured performance of developmental refrigerants in calorimetric and psychrometric environmental chamber measurements. This validation has verified that the models do give high quality predictive results.

Comparisons are shown for refrigerants R-134a, R-22, R-407C and R-410A for AC and R-404A for refrigeration. The data from these known refrigerants is helpful also for the presentation charts that show graphical comparisons of the results. Also shown are data for HFO-1234yf, R-32, and for the refrigeration cases, CO_2. R-32 is included for comparison purposes, but it is not as attractive as some of the other candidates, for several reasons. By itself it presents a greater fire hazard due to its higher heat of combustion and faster flame propagation speed. Its high heat of compression and high vapor pressure result in substantially higher discharge temperatures and condenser pressures. It offers less energy efficiency at lower evaporator temperatures. These high discharge temperatures and pressures place operating stresses on compressors and lubricants. However, because of its moderate GWP value and its refrigeration performance, it has value as an ingredient when formulating refrigerant blends, where its positive attributes can be used to advantage, and its negative attributes mitigated.

In addition to cycle modeling, other laboratory testing has been performed to evaluate properties including flammability. Flammability testing is done using the modified ASTM-681 procedure outlined by ASHRAE (2007) in Standard 34. Non flammable formulations are considered in order to demonstrate the levels of capacity or COP improvements that can be attained at different GWP levels and remain non flammable. It will be noted that Candidate DR-11 shows performance that is generally comparable to or better than that of neat HFO-1234yf. Candidate DR-9 achieves higher refrigeration capacity, but it has some temperature glide in heat exchangers, as well as a higher GWP. The other candidates are all mildly flammable – as would be defined by the ASHRAE Standard 34 Category 2L flammability, or ISO DIS-817 category 2L (ISO, 2009), similar to that of HFO-1234yf. While flammable, some of these compositions yield significantly improved refrigeration capacity or COP, with some showing performance very close to that of refrigerants R-410A or R-404A.

3.1. Residential Air Conditioning and Heat Pump Modeling Results and Discussion

While it is possible to cool or heat living space with equipment designed to use R-134a or HFO-1234yf, it may not be optimum or efficient. The HVAC industry has adopted a higher capacity refrigerant, R-410A, as the non ozone depleting global standard for this application. Significant investment has been made to develop and optimize equipment platforms to use this refrigerant. In discussions with companies that manufacture HVAC systems, requests were made for reduced GWP refrigerant options that still retained as much as possible of the performance offered by R-410A, and with physical and thermophysical properties close to that of R-410A. In response to these requests, a set of refrigerant options have been developed that have refrigeration capacities as close as possible to that of R-410A, but with a range of GWP values. It is useful to evaluate options having different GWP levels, because currently there are no regulations limiting the GWP value of refrigerants used in stationary AC. There are being proposed and discussed regulations that, if enacted, could limit or restrict the GWP values of refrigerant gases. Until there is regulatory clarity on GWP requirements for stationary AC and refrigeration, the approach of evaluating several GWP options is useful to determine the energy efficiency and capacity performance ranges that could exist if a GWP weighted regulatory approach is ultimately accepted. Ideally, any such regulations would allow some balanced GWP weighting so that high capacity and high efficiency compositions could be used.

Cycle Model results in Table 1 show that neat HFO-1234yf gives cooling capacity that is about 57 % lower than that of R-410A, when modeled at typical AC conditions. The non flammable, reduced GWP candidate DR-11 shows performance only slightly better, a 54 % drop in capacity, but with significant increases of around 7 % for COP, vs. R-410A. Candidate DR-9 gives better capacity, but still 37 % less and with a 4 % improvement of COP, as compared to R-410A, but with a temperature glide of slightly less than 4 K. It may be useful if flammability concerns over ride other considerations.

Table 1: AC cooling cycle performance of candidate refrigerants and blends

Evaporator Temperature = 7 ºC Condenser Temperature = 47 ºC Liquid sub cooling = 12 K
Suction gas superheat = 3 K Compressor volumetric efficiency = 70 %

Refrigerant Candidate	GWP (AR-4)	Temperature Glide K	Discharge Pressure kPa	Discharge Temp ºC	Capacity % Δ Vs. **R-410A**	COP % Δ Vs. **R-410A**	Flammable Rating (expected)
R-22	1810	0	1812	83	-31	6.4	1
R-407C	1774	4.8	1935	75	-30	5.0	1
R-410A	2088	0.1	2823	81	0	0.0	1
R-32	675	0	2939	102	9.7	0.3	2L
R-134a	1430	0	1222	64	-55	8	1
HFO-1234yf	4	0	1209	55	-57	6	2L
DR-11	< 600	0	<1300	<60	-54	7	**1**
DR-3	< 150	7	1850	70	-35	3.5	2L
DR-4	< 300	5	2300	< 80	-20	1.3	2L
DR-5	< 500	1	2750	< 90	0	< 1	2L
DR-9	<1500	4	1600	66	-37	4	**1**

Heat pump performance data from Table 2 for these candidates is in a similar range, with capacity reduction of 56 % for candidate DR-11, but with heating COP improvements of 5 % vs. R-410A. DR-11 offers the added advantage of having less than one third of the GWP of R-410A, a substantial reduction. There is no clear answer to how much reduction in GWP will be acceptable, even with improved COP, but candidates with only one third of the GWP value should be of interest, especially if the candidate is not flammable. DR-9 is the highest capacity non flammable composition that was developed, but its higher GWP value of near 1500 could be an issue. Candidates DR-3, DR-4, and DR-5 in the tables show performance comparisons of these mildly flammable refrigerants at stepwise increasing levels of GWP. Some of the candidates show temperature glide, as they are non azeotropic mixtures of refrigerants.

Inspection of the data shows that candidate DR-5 gives a predicted capacity match with improved COP vs. R-410A, with only 1 K temperature glide and more than 75 % reduction in GWP.

For air conditioning and heating, candidate DR-3 has less capacity, but significantly lower GWP, more than 90 % less than that of that of R-410 A for both cooling and for heating, but at a cost of higher temperature glide. It is possible that some balance of properties that include the reduction in GWP, moderate decreases in cooling and heating capacity, but a slight increase in COP could make these candidates attractive for consideration in particular heating and air conditioning applications or in specific regulatory scenarios. The other candidates on the table are less competitive in terms of performance for cooling and heating, but depending on ultimate regulations, could be interesting options to consider, especially due to their higher COP. Definition of the ultimate regulatory environment will impact the possible candidates for consideration.

Table 2: Heating Cycle Performance of Candidate Refrigerants and Blends

Evaporator Temperature = 0 ºC Condenser Temperature = 45 ºC Liquid sub cooling = 12 K
Suction gas superheat = 3 K Compressor volumetric efficiency = 70 %

Refrigerant	GWP	Temperature	Discharge	Discharge	Capacity	COP	Flammable
Candidate	(AR-4)	Glide	Pressure	Temp	% Δ	% Δ	Rating
		K	kPa	ºC	Vs. **R-410A**	Vs. **R-410A**	(expected)
R-22	1810	0	1728	86	-32	5	1
R-410A	2088	0.1	2695	84	0	0	1
R-407C	1774	4.9	1843	77	-32	3	1
R-32	675	0	2803	109	10	0.25	2L
R-134a	1430	0	1222	64	-55	8	1
HFO-1234yf	4	0	1209	55	-57	6	2L
DR-11	< 600	0	<1250	<60	-56	5	**1**
DR-3	< 150	7	< 1800	70	-36	2.5	2L
DR-4	< 300	5	2200	80	-20	1	2L
DR-5	< 500	1	~2600	~90	0	< 1	2L
DR-9	<1500	4	1700	66	-38	2.7	**1**

3.2. Refrigeration System Modeling Results and Discussion

In Table 3 are shown cycle modeling results for medium temperature (-10 ºC) evaporator conditions. This condition covers much (medium temperature) commercial supermarket and food processing operation. The cycle modeling results obtained for these cases are referenced to an incumbent refrigerant widely used in commercial refrigeration, R-404A. Similar to the air conditioning and heating cases, it was possible to develop compositions that come very close in terms of delivering refrigeration capacity and COP to the performance of R-404A.

Note for example candidate DR-7. For medium temperature refrigeration it shows discharge pressure, capacity and COP that are all very close to the incumbent R-404A. These candidates have GWP values of less than 7 % of that of R-404A, a reduction of more than 93 %. While the COP is slightly better than that of R-404A, there are other considerations that could impact energy efficiency performance. For example, the predicted compressor discharge temperature is higher than that of R-404A. If it were to become necessary to employ compressor head cooling, then overall efficiency would be impacted. This needs to be explored with designers of refrigeration systems to assess possible impact and to optimize the balance of COP, capacity, discharge temperature, and GWP value.

Candidates DR-11 and DR-9 are again interesting in that these are non flammable candidates. DR-11 has the potential to be used in systems where R-134a is currently being used, and could offer a 58 % or more reduction of the GWP versus R-134a. These gases have similar refrigeration properties, but more capacity than R-134a. The higher capacity could translate to less compressor run time to achieve the desired cooling set point, and hence less energy consumption.

Looking further at the system data, one sees a much wider range of trade offs in terms of volumetric capacity and COP, as well as GWP. It may be possible to use a DR-7 for example, or even DR-4, and make only small modifications in refrigeration system design, and yet gain environmental advantages. One could achieve more than 96 % reduction in GWP, versus R-404A, with possible gains in system efficiency, and little temperature glide, as in the case of DR-3 or DR-4, for example.

Table 3: Medium Temperature (- 10 ºC) Refrigeration Cycle Model Comparisons

Evaporator Temperature = -10 ºC Condenser Temperature = 40 ºC Liquid sub cooling = 6 K
Suction gas temperature = 18 ºC Compressor volumetric efficiency = 70 %

Refrigerant or Candidate	GWP AR-4	Temp. Glide K	Disch Pressure kPa	Disch Temp ºC	Capacity % Δ vs **R-404A**	COP % Δ vs **R-404A**	Flammable Rating (expected)
CO2	1	0	9172	154	378%	-38%	1
R-404A	3922	0.4	1833	85	0%	0%	2
R-32	675	0	2485	144	45%	-3%	2L
R-22	1810	0	1532	117	-8%	4%	1
R-134a	1430	0	1017	90	-43%	8%	1
HFO-1234yf	4	0	1016	77	-43%	7%	2L
DR-11	< 600	0	<1100	<85	-40%	7%	**1**
DR-3	< 150	<7	<1600	92	-13 %	3 %	2L
DR-4	< 300	5	< 2000	105	9%	0	2L
DR-6	< 400	< 3	< 2200	<115	23%	-1%	2L
DR-7	< 250	6	< 1850	101	3%	0	2L
DR-9	<1500	4	~ 1500	88	-16%	3%	**1**

4. MEASURED SYSTEM PERFORMANCE IN AIR CONDITIONING

Validation of the theoretical cycle modeling results for air conditioning was done by running cooling and heating tests in an instrumented mini-split AC/Heat Pump unit. Two series of testing was done. First a round of tests was done with neat HFO-1234yf, as straight drop in, then again with modifications made to the system to reduce pressure drop. The test unit was a commercial Toshiba model RAS-281BDR, with rated capacities of 2.8 KW for cooling and 3.2 kW for heating, operated in an environmental chamber. R-410A was run first to establish base line operation, then the refrigerant was replaced with the candidate fluids. In a second round of testing the higher capacity fluids DR-4, and then DR-5 were evaluated. The DR-4 and DR-5 were tested only in actual “Drop In” tests. No modifications were made to the equipment.

When neat HFO-1234yf was charged to the R-410A designed AC / heat pump system, performance was, as expected, not as good as was obtained with R-410A. Even though, the calculated LCCP was better (less than) that for R-410A by 5 %. When the system was modified to increase heat exchanger effectiveness and to reduce pressure drop, the performance with HFO-1234yf improved, but still did not match the 410A base line performance. The modifications did result in further improvement of LCCP, to as much as 20 % lower than the R-410A base line. Details of modifications and performance for neat HFO-1234yf may be the subject of a future paper. In this report the focus will remain on performance with refrigerant candidate blends DR-4 and DR-5, for which data are summarized in the figures to follow.

Figure 1 shows results from our theoretical cycle model calculations. This is an ideal cycle model that does not take into account pressure drop, heat transfer, or other real system effects. Figure 2 shows measured results from the laboratory testing of the AC/Heat Pump unit. Results are scaled to R-410A results for every case. The cycle model predicts that DR-4 and DR-5 have COP values for heating and cooling that match R-410A within one per cent. DR-4 is predicted to lose 18 to 19 % in capacity, while DR-5 is predicted to match the capacity of 410A. The measured data shows the actual system performance of both candidates to be better than predicted in the cycle model. COP values exceed the model predictions for heating and for cooling for both candidates. Using the measured energy performance, the APF (Annual Performance Factor) was calculated. APF is the sum of weighted cooling season load plus heating season heat load(for Tokyo climate conditions) divided by the sum of cooling season energy consumption plus heating seasonal energy consumption, all as measured at standard rating points. The result of this calculation is shown in Figure 2. It is seen that DR-4 has APF 3 % lower than R-410A, and DR-5 has APF 5 of 3 % better than R-410A. Finally, Life Cycle Climate Performance was calculated for each case, R-410A, DR-4, and DR-5, using the same assumptions for leakage and refrigerant recovery, but taking credit for the lower energy consumption and lower direct GWP values of DR-4 and 5. The LCCP for DR-4 was 21 % less than R-410A, and LCCP for DR-5 was calculated to be 24 % less than for R-410A. These are superior results.

The measured system results show that indeed, the performance of these two candidate blends is such that DR-5 could be used as a drop in replacement in this system and give performance superior to that of R-410A. The GWP of DR-5 is near 500, about 76 % less than that of R-410A, but its energy performance and LCCP are superior. DR-4, with GWP of less than 300, or about 86% less than R-410A, did not perform as well in this drop in test; however its performance is quite interesting. One could suppose that with some light system modification, such as enlarged suction line size and more heat exchanger surface, or perhaps more compressor displacement, that performance could come quite close to that of R-410A, and still retain a relatively compact package size.

Clearly more testing needs to be done in systems of different sizes and capacities and types, but these initial test results are quite promising. Testing is under way in several other types and sizes of equipment, so it is expected that more results will be forthcoming in these areas.

Figure 1: Modeled Refrigerant Performance

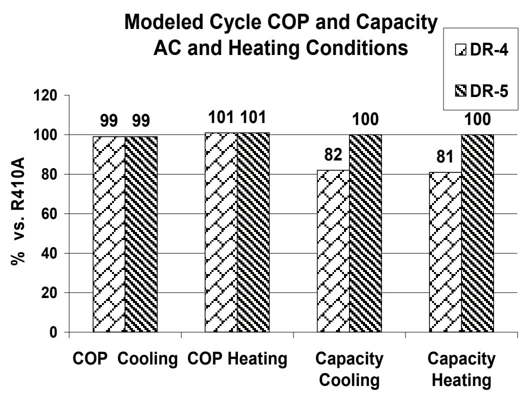
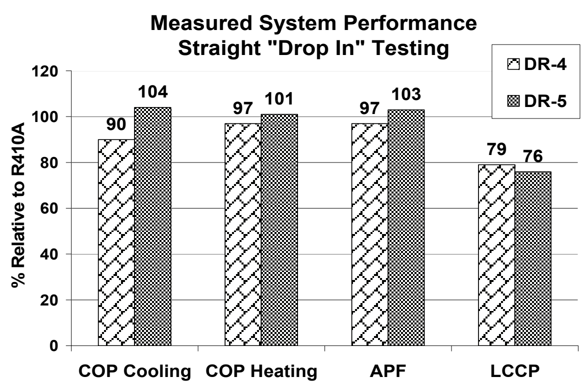


Figure 2: Measured Refrigerant Performance



5. DISCUSSION AND CONCLUSIONS

This work shows that it is possible to design refrigerants with reduced GWP values. One must consider several options and trade offs involved in the design of new, reduced GWP refrigerants using HFO-1234yf and other refrigerant molecules in order to find the most appropriate solutions. It may be possible to use existing equipment designs while gaining significant reduction in GWP as well as reductions of LCCP versus incumbent refrigerants such as R-134a, R-404A and R-410A. The results reported here show that the lowest GWP refrigerant used in the air conditioning and heating tests, neat HFO-1234yf, while giving LCCP less than that of R-410A, never the less did not show as high APF or as low LCCP values as did the higher GWP rated refrigerants DR-4 and DR-5. Of these, the DR-5, with GWP somewhat less than 500, gave the best overall energy and LCCP performance. More data, especially transport property measurements, are necessary to allow complete system modeling, and these data are currently being developed in several laboratories. However, cycle model calculations give high confidence that improved performance, reduced GWP refrigerants are possible and viable. The experimental laboratory results strongly reinforce the modeling data that does exist for these candidate refrigerants. If regulations allow use of these new refrigerants in conventional equipment designs, it should be possible to retrofit existing equipment to use these reduced GWP fluids. Such an approach could allow users to transition more quickly into using more environmentally sustainable, reduced GWP refrigerants and reduce the LCCP of existing systems. The candidates with reduced GWP and low or zero temperature glide are especially attractive with respect to facilitation of transition away from high GWP refrigerants. Candidates with higher values of temperature glide may be better suited for use in new equipment designs that employ heat exchangers that mitigate temperature glide effects.

Some observations bear reiteration with respect to reducing the ultimate environmental impact of refrigeration. The first is that design, use, service practices and end of life decommissioning must be focused toward elimination of any loss of refrigerant to the atmosphere. It is still necessary to use the refrigerant that offers the best energy efficiency and hence the lowest LCCP. The energy consumed by the equipment can be minimized by use of high COP refrigerants, and this does much to reduce the environmental impact. Finally, until a clearly defined regulatory environment is in place there will be uncertainty about which refrigerants and what refrigerant properties are most important or even allowable. Some well intentioned regulatory proposals intended to mitigate climate impact of leaked refrigerant could be counter productive if it drives the industry toward use of less effective refrigerants. It is hoped that this analysis of these reduced GWP refrigerant options will he helpful in defining some of the parameters that could be impacted or supported if balanced, GWP weighted, or a LCCP based regulations were implemented, and not an arbitrarily defined cap on allowable GWP values.

REFERENCES

ASHRAE/ANSI Standard 34-2007: *Designation and Safety Classification of Refrigerants*, American Society of Heating, Refrigeration, and Air Conditioning Engineers, Atlanta, GA.

Downing, R. C., 1988, *Fluorocarbon Refrigerants Handbook*, Prentice Hall, Inc

ISO/IEC DIS 817, 2009, *Refrigerant-Number Designation, Draft International Standard*, International Organization for Standardization, Geneva, Centrifugal Chillers", Switzerland.

Kontomaris, K. and T. J. Leck, "Low GWP Refrigerants for ASHRAE 2009 Annual Conference, June 20-24, 2009, Louisville, Kentucky.

Kontomaris, K., T. J. Leck and J. Hughes, "Low GWP refrigerants for air conditioning of large buildings", 10th REHVA World Congress on "Sustainable Energy Use in Buildings", Antalya, Turkey, May 9-12 (2010)

Leck, T.J. "Evaluation of HFO-1234yf as a Potential Replacement for R-134a in Refrigeration Applications" Proceedings. *3rd Conference on Thermophysical Properties and Transfer Processes of Refrigerants*, IIR and NIST, Boulder, Colorado June26, 2009

Lemmon, E.W., Huber, M.L., and McLinden, M.O., 2007 REFPROP Reference Fluid Thermodynamic and Transport Properties, *NIST Standard Reference Database 23*, Version 8.0, National Institute of Science and Technology, Boulder, CO, USA

Minor, B.H., and Spatz, MA, Evaluation of HFO-1234yf for Mobile Air Conditioning: *Proceedings of 2008 SAE World Congress*, Detroit, MI April 14, 2008

Nielsen, O.J., Jafadi, M.S., Sulback Andersen M.P., Hurley M.D., Wallington, T.J., Singh, R., 2007 Atmospheric Chemistry of CF3CF=CH2: Kinetics and Mechanisms of gas phase reactions with Cl atoms, OH radicals, and O_3, *Chemical Physics Letters* 439 (2007) 18-22

UL Standard 2182, 2006, *UL Standard for Safety of Refrigerants*, 2nd Edition, Underwriters Laboratories, Northbrook, IL, 2006

Wilson, D.W, and Leck, T.J., 2008, *Application to ASHRAE Standard 34 for Designation and Safety Classification of HFO-1234yf*, Honeywell International, Buffalo, New York, and DuPont Fluoroproducts, Wilmington, Delaware.

Yokozeki, Akimichi, 2008, Unpublished DuPont Laboratory Data and computer code.

Yamaguchi, Hiroichi, 2010, Personal discussions and unpublished laboratory data from Toshiba-Carrier testing.

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